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MEMORANDUM REPORT NO. 1970

YAWING MOTION OF A BULLET AFTER PENETRATING A THIN PLATE

by

Walter F. Braun

April 1969

U.S. ARMY ABERDEEN RESEARCH AND DEVELOPMENT CENTER
BALLISTIC RESEARCH LABORATORIES
ABERDEEN PROVING GROUND, MARYLAND

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BALLISTIC RESEARCH LABORATORIES

MEMORANDUM REPORT NO. 1970

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YAWING MOTION OF A BULLET AFTER PENETRATING A THIN PLATE

Walter F. Braun

Exterior Ballistics Laboratory

RDT&E Project No. 1T262301A201

ABERDEEN PROVING GROUND, MARYLAND

B A L L I S T I C   R E S E A R C H   L A B O R A T O R I E S

MEMORANDUM REPORT NO. 1970

WFBraun/eb
Aberdeen Proving Ground, Md.
April 1969

YAWING MOTION OF A BULLET AFTER PENETRATING A THIN PLATE

ABSTRACT

When a bullet penetrates a thin plate and emerges relatively undamaged, the period of the subsequent yawing motion can be predicted from a knowledge of the physical constants of the bullet, the spin, the density of the medium after penetration and the static moment coefficient. The equations used to predict this motion are given. Several examples of the predicted motion are compared with empirical data. The effects on the period and the magnitude of yaw of small changes in the bullet characteristics due to impact on the plate are discussed, emphasizing the importance of obtaining sufficient data to describe the complete yaw period and sufficient information on the physical integrity of the bullet after impact. The importance of imparting the correct bullet spin when simulating real down-range test conditions is discussed. A comparison of test data taken under different spin conditions is given.

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LIST OF SYMBOLS

$C_{M\alpha}$	static moment coefficient
d	reference body diameter, maximum diameter, mm
I_x	axial moment of inertia, gm - cm^2
I_y	transverse moment of inertia, gm - cm^2
K_j	modal amplitude of yaw
k_t	transverse radius of gyration
ℓ	reference length, for small arms bullets, ℓ = d, mm
L	wave length of the yawing motion, calibers
m	mass, grams
M	$\frac{\rho S \ell}{2m} k_t^{-2} C_{M\alpha}$
p	axial component of the angular velocity, rad/sec
P	$\left(\frac{I_x}{I_y}\right) \frac{p\ell}{V}$ rad/cal
S	reference area, the maximum body cross-sectional area
s_g	gyroscopic stability factor $s_g = P^2/4M$
s	dimensionless arclength along trajectory $\frac{1}{\ell} \int V\, dt$ (for ℓ = d, s is in calibers) $s \cong x_1/d$
V	magnitude of the velocity vector, m/sec
φ_j	modal orientation, radians
φ_j'	modal frequency, derivative with respect to s φ_1' nutational, rad/cal φ_2' precessional, rad/cal
ξ	complex yaw, $\frac{v + iw}{V} = \delta e^{i\theta} \cong \beta + i\,\alpha$, in missile-fixed coordinates
α	angle of attack
β	angle of sideslip

LIST OF SYMBOLS (CONTINUED)

ν nondimensional spin $\frac{p\ell}{V}$, rad/cal

ρ air density

Subscripts and Superscripts

M at muzzle

$(\ )'$ derivative with respect to s

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I. INTRODUCTION

The effectiveness of armor against small arms is increased when the magnitude of the bullet's yaw at impact is large. Thus it is possible to improve the protection-weight ratio of armor by using a tipping plate to cause the bullet to have high yaw on impact with the main armor protection. The main function of the tipping plate is to impart a large angular impulse to the bullet, causing rotation about the transverse axis. The energy loss to the tipping plate is generally small compared with the main functional value of the tipping plate phenomena. The effect of the impact on the bullet shape and mass distribution can affect the response of the bullet to the impulsive torque imparted by the plate.

Tipping plates exist naturally as the structural members of aircraft skin and vehicular panels, or the plates may be deliberately added as part of the armor system. In order to optimize the benefits from the phenomena and to evaluate the effectiveness of various materials under different circumstances, a complete investigation should include:

1. A study of penetration mechanics to understand the impulsive forces and moments imparted to the bullet during penetration of the tipping plate as a function of:

    a. Tipping plate material.

    b. Attitude of the plate to the trajectory.

    c. Flight variables of the bullet; velocity, stability, yaw and yawing velocity at impact.

    d. Bullet shape and construction.

2. A study of the flight behavior of the bullet after penetration of the plate, including the effects of the impulsive moment and of changes in bullet shape and dimensions on the yawing motion.

The cumulative study would determine the distances necessary to develop significant yaw magnitudes as a function of bullet and tipping plate parameters.

Several investigations for an evaluation of a large number of tipping plate materials and conditions of impact have been made by various researchers.[1,2,3*]

The purposes of this report are to investigate the flight behavior after impact and to compare the observed yawing motion with predictions developed from existing exterior ballistic theory. An attempt will be made to explain some of the apparent anomalies that so often occur in tests of this nature where insufficient empirical data is obtained.

II. THE EFFECT OF THE PLATE ON THE BULLET

In the penetration phenomena, the plate will to some degree produce five effects on the bullet. The plate will:

1. Exert an axial force on the bullet. This produces a loss in velocity. If the angular momentum vector remains unchanged, this velocity loss produces a decrease in the wave length of the yawing motion. The bullet does not travel as far in the time it takes to perform one oscillation. This same effect is produced by the loss in velocity due to the drag force.

2. Exert a transverse force on the bullet. This produces a velocity component at right angles to the original trajectory. Over the short distances of practical interest in this phenomena, less than three meters past the tipping plate, this velocity component is the most significant factor in the deflection of the bullet from the original trajectory.

3. Exert an axial moment on the bullet. This produces a loss in the spin velocity. This same effect exists as the bullet flies thru the air, as represented by the spin deceleration moment coefficient. The result is an increase in the yaw period. In air the loss in spin velocity is generally small and the net result of the combined axial force and moment is a shortening of the yaw period.

*References are found on page 34.

4. Exert a transverse moment on the bullet. This produces the impulsive torque that develops the large rotational motion about the transverse axis of the bullet. Determination of the magnitude of the torque imparted to the bullet involves a study of the penetration mechanism which is beyond the scope of this test. However, the period of yawing motion should be predictable. For a specific value of impulsive torque and a measured bullet reaction, we should be able to predict the ratios of the magnitudes and periods of yaw for small changes in bullet parameters.

5. Damage the bullet to some extent. To use exterior ballistic theory to describe the bullet motion, the physical constants and aerodynamic coefficients must be known. To predict the yaw period, the important factors are the axial and transverse moments of inertia, and the static moment coefficient. Numerical values for these constants are usually available for the unfired bullet and for the bullet in flight at low magnitudes of yaw. It is difficult to predict exactly how these values will be changed by the impact mechanism. A general evaluation of bullet damage can be made from the spark shadowgraphs of the bullet after impact.

In some instances it is possible to infer from the pictures which of these physical parameters have changed. In other instances, where the spin and yaw period are known, only the cumulative effect of the changes in all three parameters can be discussed.

There is some evidence from the limited amount of data in this test that for bullets with steel cores, the yaw period is decreased slightly by the action of the plate on the bullet. This could be caused by the steel core driving forward into the copper shell, shortening the moment arm and decreasing the static moment coefficient and thus the yaw period. There is also some evidence that for lead alloy bullets the yaw period is increased. We might expect the swaging action of the plate on the bullet to elongate the bullet and increase the transverse moment of inertia, with a corresponding decrease in the axial moment. These factors lengthen the yaw period.

III. SIMULATION OF DOWN-RANGE TESTS

Generally real targets are some distance from the gun muzzle. Testing at these real down-range conditions is inconvenient even when we know at what distances we should test. The most obvious change in bullet flight parameters with range is the striking velocity. A common technique for simulating an impact at some distance from the gun muzzle is to reduce the amount of powder in the cartridge case, lowering the muzzle velocity. The target can be located reasonably close to the muzzle. Some tests have been conducted at standard muzzle velocity, with the tipping plate close to the muzzle[1]. Other tests have been fired at high, medium and low muzzle velocities[2]. Neither of these procedures properly simulate the conditions at realistic impact velocities or after the impact. The disadvantage of this type of test is that the bullet does not have the correct spin at the simulated impact velocity. The effect of this improper simulation of the bullet spin is reflected in the development of a period and magnitude of yaw that are different from the actual conditions at long ranges. We should be prepared to simulate in our test the real range conditions or else be able to convert the test data to that which would be observed under actual impact.

The problems in simulation for this type of experiment involve matching the velocity, the yaw, the orientation of yaw, the yawing velocity, and the bullet spin at impact on the tipping plate at the selected test distance from the muzzle. All of these parameters are not of equal importance in establishing the motion after impact on the tipping plate. Some will affect the induced torque and thus the magnitude of yaw. Others will have more affect on the frequency of the yawing motion and the response of the bullet to the induced torque.

Considering the large number of small arms bullets that exist and the variety of conditions under which they are fired, it is difficult to generalize as to what impact conditions should be expected. To keep the discussion within reasonable bounds, the bullets can be divided into two categories. One category would include those bullets starting their trajectories with a gyroscopic stability factor of 1.7 or

less. This group would include the M-59 and the M-193 as good examples. The second group includes bullets with higher stability factors, such as the cal .30 Ball M2, (s_g = 3.2) and the 14.5mm API, (s_g = 4). In all cases for a particular bullet, s_g also depends on the twist of rifling of the gun used and increases with range.

For a test location close to the gun muzzle, the simulation of any impact velocity is a routine procedure. Usual hand loading techniques and a few proof rounds will establish adequate charge-velocity data for muzzle velocities down to the point where the bullet sticks in the gun barrel.

When firing at a reduced muzzle velocity, simulating the bullet spin at the desired impact velocity requires a gun tube with the proper twist of rifling. Approximate values of the bullet velocities and spin at any range are computed from data on the standard muzzle velocity, the standard twist of rifling, the physical dimensions of the bullet, the air density, the drag coefficient and the spin deceleration coefficient.

Simulation of the yawing motion required some knowledge of the conditions that exist near the gun muzzle and at long ranges. Close to the gun muzzle, the amplitude of the yaw is a function of initial conditions and the stability factor of the bullet. The initial conditions are influenced by the type of gun, the condition of the gun and the use of flash hiders or muzzle brakes. The fast and slow components of the yaw are generally equal in size and the magnitude of the yaw will periodically change from its maximum to its minimum value of near zero. The length of the period depends on the factors that make up the gyroscopic stability factor.

At distances over 15,000 calibers from the muzzle (85 meters for the M-193 bullet) the yawing motion of some small arms bullets approaches a limit cycle. The fast component of yaw will have damped. A circular motion of slowly damping or constant amplitude slow mode of yawing motion will exist.

For a gun-bullet system that shoots a consistent yaw pattern, it should be possible to simulate any yaw impact magnitude up to the maximum value, at a location close to the gun muzzle. In some instances it may be necessary to use yaw inducers, since the magnitude of the yaw at long ranges can be larger than the maximum value near the gun. It would be difficult to simulate the yawing velocity observed at long ranges. Some tests have shown that small incident yaws at impact have little effect on the yaw after the tipping plate[1]. There is also some evidence that the magnitude of the yaw induced by the tipping plate is not a function of yawing velocity at impact[1].

IV. THE YAWING MOTION OF THE BULLET

These tests and this discussion are limited to statically unstable bullets spinning fast enough so that they are gyroscopically stable. The problem is to predict the distance to the maximum yaw after an impulsive torque has been applied to the bullet. The derivations of the equations used in discussing the motion can be found in any standard text on exterior ballistics[4].

Since we are concerned with only the first half-cycle of yawing motion, which for most small arms bullets occurs within 4 meters after the impulsive torque is applied, several simplifying assumptions are made. Damping and gravity terms are neglected and the coefficients of the differential equations are linearized. The remaining terms are the linear static moment term and a gyroscopic spin term. The equation of the yawing motion becomes:

$$\xi'' - iP\xi' - M\xi = 0$$

where

$$M = \frac{\rho S \ell}{2m} k_t^{-2} C_{M\alpha}$$

$$P = I_x / I_y \, \nu$$

The solution is the sum of two rotating vectors:

$$\xi = K_1 e^{i\varphi_1} + K_2 e^{i\varphi_2}$$

The amplitudes of the two arms of the disturbance due to the impulsive torque are K_1 and K_2. The orientation of these amplitudes change at constant rates φ_1' and φ_2'.

The maximum magnitude of yaw, $|\xi|_{max}$, occurs when $\varphi_1 = \varphi_2$, so that K_1 and K_2 add. The minimum value of yaw occurs when φ_1 and φ_2 are 180^o out of phase, at which point the magnitude of yaw is the difference of K_1 and K_2. The frequency of the yawing motion is equal to the difference of the rates, $\varphi_1' - \varphi_2'$. The wave length of the yawing motion is given by:

$$L = \frac{2\pi}{\varphi_1' - \varphi_2'} \quad \text{calibers} \tag{3}$$

Since a minimum value of yaw occurs at the tipping plate, the distance from the plate to the first maximum yaw would be one-half of the period. Now the yawing motion of a gyroscopically stable bullet with only a linear static moment acting is described by two vectors, each rotating at a constant angular velocity[4].

$$\varphi_j' = (1/2)\left[P \pm \sqrt{P^2 - 4M}\right] \tag{4}$$

The difference of the rates is

$$\varphi_1' - \varphi_2' = \sqrt{P^2 - 4M} \tag{5}$$

The distance to the first maximum yaw from the tipping plate is

$$\frac{L}{2} = \pi/\sqrt{P^2 - 4M} \text{ calibers} \tag{6}$$

The gyroscopic stability factor is

$$s_g = \frac{P^2}{4M} > 1 \tag{7}$$

Thus the half-period of yaw can also be written as:

$$\frac{L}{2} = \pi/P\sqrt{1 - \frac{1}{s_g}} \tag{8}$$

Substituting the expressions for M and P, we see the effect of the various constants on the period.

$$\frac{L}{2} = \frac{\pi I_y}{\left[I_x^2 \nu^2 - 0.5 \pi \rho d^5 I_y C_{M\alpha}\right]^{1/2}} \text{ calibers} \qquad (9)$$

As the stability factor approaches 1 the length of the period increases. In the region $s_g = 1.05$ to 1.2, small variations in bullet shape and mass distribution give large variations in the period length. When the stability factor is larger there is less variation in period length with small changes in bullet parameters.

In the computations used in this report, the numerical values for the moments of inertia and the static moment coefficient are for the bullet before firing and for range firings at small yaws. The values that should be used are those for the bullet after penetrating the plate. The problem of estimating how the bullet parameters change from "before the plate" to "after the plate" conditions becomes more important for computing the period when the stability factor is low as in the M-61 bullet.

V. EXPERIMENT

A limited number of rounds of several types of small arms ammunition were fired in the Aerodynamics Range[5], Figure 1, to test the hypothesis that the location of the first maximum yaw after the tipping plate can be predicted in those instances where the damage to the bullet is negligible and the yaw at impact small.

The rounds were fired in two programs. The 14.5 mm API bullet was tested in the first firing program. In the second program the cal .50, cal .30, the 7.62 mm and the 5.56 mm bullets were fired. There were minor differences in the experimental setup in the range for the two programs.

For all rounds, the velocity of the bullet and the yawing motion before impact were obtained from the spark photography stations in the

range. The spark station is a precisely surveyed camera that records an orthogonal pair of silhouette images of the bullet. The location of the center of gravity of the bullet in flight in the range coordinate system is obtained from the pictures to an accuracy of ± 0.5 mm. The attitude of the bullet is measured to an accuracy of ± 10 minutes of arc. The time elapsed between selected successive pictures is measured with time interval counters, accuracy ± 1 microsec.

The tipping plate was supported in a metal frame that could be adjusted to set the plate at the selected angle to the usual (horizontal) range trajectory. The plate angle was measured with a gunners' quadrant. The unsupported area of the plate at the impact region was at least 1/2 meter by 1/2 meter. The plate was shifted between rounds so that the distance between successive impacts on the plate was at least 7 cm. Two types of Duraluminum plate were used in the test. The type and thickness are listed in Table II and III.

Data after the plate was taken by both yaw cards and spark photography stations. Figure 2 shows the yaw card and station arrangement after the tipping plate for the two programs. Since the 14.5 mm API was incendiary no attempt was made to obtain spark photography data after the tipping plate. The incendiary action generated enough light to make this type of photography impractical. For all the other rounds fired, two orthogonal sets of spark photographs were obtained after impact to supplement the yaw card data. These photographs with their time measurements gave the velocity components after impact, the bullet yaw and orientation and the silhouette images from which estimates of projectile deformation could be made.

The yaw cards were single weight, glossy photographic paper stapled to wood frames that held the paper normal to the trajectory before impact. Thus the yaw and orientation angle measurements were referenced to the fixed range coordinate system while the computations for the yaw period are based on a missile-fixed reference system. However, the lateral deflections of the bullets were small. The angle between the trajectory and the range coordinate system was generally less than 2°

for yaw angles of about 45°. For smaller yaw angles the deflections from the original trajectory were less.

The yaw magnitude and orientation were obtained from measurements of the length and angle of the elliptical hole punched in the yaw card. The relationship of the yaw to the major axis of the oblong hole was obtained by rotating a silhouette image of the bullet through selected angles on a grid and measuring the projected lengths of the bullet.

For large angles of yaw, the data should be accurate to $\pm 1^{\circ}$. For angles less than 5°, it is difficult to evaluate the yaw magnitude and the error may be as large as $\pm 2^{\circ}$ in the case of the caliber .50 bullet[6]. An additional difficulty with the yaw card measurement technique is that after impact on the plate the bullet does not look exactly like the bullet used to make the yaw - major axis plot. This will degrade the accuracy of the yaw measurements. Confidence in the overall accuracy of the yaw card technique is established by the agreement of yaw card and spark photography station data.

A further disadvantage of the yaw card technique is that each card imparts an additional impulsive moment to the bullet. For large bullets like the 14.5 mm API, with large gyroscopic stability factors (3 to 4), the effects of the yaw cards can be ignored for the present purpose. For small bullets like the 5.56 mm, M-193, with a low stability factor (less than 1.7), the effects of the impulsive moment imparted to the bullet by the yaw card have produced small but measurable increases in the magnitude of yaw and the apparent yaw period. It is important when using yaw cards in this type of test to compute the approximate location of the maximum yaw and to distribute a minimum number of cards along the trajectory to get the required data. For the 5.56 mm bullet, it would appear that the only acceptable technique for obtaining yaw measurements are by photographic means.

The bullets were fired from standard rifles, Mann barrels or gun tubes with a special high twist of rifling. Since only a limited number of gun tubes were available with special rifling, it was not always

possible to match the correct bullet spin when simulating at close range the impact velocities that occur at long ranges.

A list of the types of ammunition used in the test is given in Table I, which includes pertinent data about the physical measurements[7], standard muzzle velocity and spin at the muzzle when fired from the standard gun. A list of the rounds fired, with velocity, tipping plate, yaw, period and spin data is given in Table II and III. Details and discussion of the experimental data obtained with each bullet type is given in the following section.

VI. RESULTS

A. 14.5 mm API

Since there were no available aerodynamic force and moment data for this round, the tipping plate was located at the end of the Aerodynamics Range, 1.28 meters after the last spark station, 90 meters from the gun muzzle, in order that complete data could be obtained before impact. Figure 2 shows the location of the tipping plate and yaw cards in the range. Table I gives the physical measurements for the round. Figure 3 shows a silhouette of the projectile in flight.

The technique for obtaining the aerodynamic coefficients over the range of Mach numbers encountered in the complete trajectory requires firing rounds at several muzzle velocities. Each round gave data at one mid-range velocity in the 90 meter test facility. Thus in combining the two efforts, the tipping plate data was obtained at impact velocities from 1029 to 434 m/sec.

For eight of the rounds, the incendiary functioned between 1 and 1.3 meters after the tipping plate. On four of these eight rounds it was not possible to observe the magnitude or the location of the maximum yaw because the incendiary action destroyed some of the yaw cards. On four rounds there was no evidence of the incendiary functioning up to

TABLE I. PHYSICAL MEASUREMENTS OF SMALL ARMS BULLETS

	14.5 mm API	Cal .50 Ball M2	Cal .30 Ball M2	7.62 mm M-80	7.62 mm M-59	7.62 mm M-61	5.56 mm M-193
Weight - grams	63	45.2	9.77	9.45	9.63	9.55	3.58
Nominal Gun - cal	30	-	-	-	-	-	-
Rifling - in.	-	15	10	12	12	12	12
ν - rad/cal	.209	.213	.193	.161	.161	.161	.116
Standard Muzzle velocity m/sec	1000	853	853	868	868	868	1000
Ref. Diam. - mm	14.88	12.95	7.82	7.82	7.82	7.82	5.56
I_x - gm cm^2	14.45	8.09	.612	.574	.625	.619	.118
I_y - gm cm^2	70.04	90.03	4.41	4.03	6.14	6.06	.760
I_x / I_y	.206	.090	.139	.142	.102	.102	.155
Center of Mass from Base - cal	1.10	1.91		1.40	1.66	1.65	1.32

TABLE II. CAL .30 BALL M2, 7.62 mm M-80, M-59

Rd. No.	Velocity m/sec At Muzzle	Velocity m/sec At Impact	Velocity m/sec After Plate	Dural Plate Angle (Deg)	Dural Plate Type	Max. Yaw (Deg)	Location From Plate (meters)	Spin rad/cal At Muzzle	Spin rad/cal After Plate
Caliber .30 Ball M2 - - Plate Thickness 1.6 mm									
8013	546	536	524	20	2024-0	33	1.1	.19	.20
8014	486	477	463	10	2024-0	42	1.1	.19	.20
8015	472	462		10	2024-0	39	1.1	.19	
8631	543	531	519	10	2024-0	11	.64	.32	.34
8632	531	520		20	2024-0	42*	.64	.32	
8633	526	510	497	20	2024-0	17	.64	.32	.34
8634	537	526	513	20	2024-0	13	.64	.32	.34
7.62 mm M-80 - - Plate Thickness 1.6 mm									
8016	614	604	592	10	2024-0	40	1.5	.16	.17
8017	618	607	598	5	2024-0	27	2.1	.15	.17
8018	627	615	604	5	2024-0	31	2.1	.16	.17
7.62 mm M-59 - - Plate Thickness 1.6 mm									
8019	634	624	618	5	2024-0	45	3.3	.16	.17
8020	622	610	606	5	2024-0	44	3.3	.16	.17
8021	583	570	561	10	2024-0	45	3.1	.16	.17
8022	574	562	557	10	2024-0	53	3.1	.16	.17
8636	546	533	515	20	2024-0	35	.74	.32	.34
8637	568	557	545	20	2024-0	30	.74	.32	.34
8638	594	572	568	10	2024-0	17	.74	.32	.34
8639	544	538	523	10	2024-0	16	.74	.32	.34

TABLE III. 5.56 MM M-193, 7.62 MM M-61, Cal .50 BALL M2

Rd. No.	Velocity m/sec At Muzzle	Velocity m/sec At Impact	Velocity m/sec After Plate	Dural Plate Angle (Deg)	Dural Plate Type	Max. Yaw (Deg)	Location From Plate (Meters)	Spin rad/cal At Muzzle	Spin rad/cal After Plate
5.56 mm M-193 - - Plate Thickness 1.6mm									
8007	736	721	678	20	2024-0	30	2.4	.12	.13
8008	811	774	761	20	2024-0	29	2.4	.12	.12
8009	586	558		20	2024-0	70	.9	.12	
8010	557	542*		20	2024-0	60	.9	.12	
8011		740		20	2024-0	40	2.4	.12	
8012	484	465	411	20	2024-0	60	.6	.12	
7.62 mm M-61 - - Plate Thickness 1.6 mm									
8023	617	607	599	10	2024-0	48	2.4	.16	.17
8024	614	602		10	2024-0	47	2.4	.16	
Cal .50 Ball M2 - - Plate Thickness 3.2 mm									
8625	625	616	611	20	6061T6	40	2.6	.21	.22
8626	609	600	585	10	6061T6	45	2.5	.21	
8627	629	618	599	10	6061T6	47	2.4	.21	
8628	622	612*	606	10	2024-0	35	2.9	.21	
8629	617	607	600	10	2024-0	20	2.9	.21	

TABLE IV. 14.5 MM API - - PLATE THICKNESS 3.2 MM

Rd. No.	Velocity m/sec At Muzzle	Velocity m/sec At Impact	Velocity m/sec After Plate	Dural Plate Angle (Deg)	Dural Plate Type	Max. Yaw (Deg)	Location From Plate (Meters)	Spin rad/cal At Muzzle	Spin rad/cal After Plate
7762	1057	1029		30	Dural	18*		.21	
7764	995	962		30	Dural	20*		.21	
7763	987	959		30	Dural	20	1.2	.21	
7758	980	950		30	Dural	22	1.2	.21	
7759	979	947		30	Dural	29*		.21	
Pf.2		911		30	Dural	16	1.2	.21	
Pf.1		847		30	Dural	26	1.2	.21	
7756	823	795		30	Dural	32*		.21	
7755	821	792		30	Dural	30	1.3	.21	
7757	764	734		30	Dural	31	1.2	.21	
7761	534	510		30	Dural	11	1.3	.21	
7765	458	434		30	Dural	13	1.4	.21	

*Estimated

3.5 meters, at which point the round impacted on 7.5 cm of armor plate and was destroyed.

Graphs of the magnitude of yaw vs. distance are given in Figures 4 and 5. The data is tabulated in Table IV.

All rounds developed their maximum yaw at about the same distance from the tipping plate, 1.2 meters. At the lower velocities there is a small increase in the half-period distance probably due to the increase in the static moment coefficient. The location of the maximum yaw agrees with the computed values for the impact conditions.

However only those rounds fired at standard muzzle velocity had the proper spin on impact at the tipping plate. Since the only gun available for this program had a twist of 1 turn in 30 calibers, the bullet spin was not simulated at the lower velocities. All other rounds had less than normal spin at the impact velocity and thus the observed period of yaw is larger. The location of the first maximum yaw after impact for rounds fired at standard muzzle velocity and impacting at lower velocities was computed using estimates of the spin at impact from the ratio of the muzzle velocity to the impact velocity. These data are given in Figure 6. The observed half-period of yaw for rounds fired at reduced muzzle velocity from the same gun are also shown in the same figure. This graph stresses the importance of properly simulating conditions at impact or allowing for the conditions of the test in evaluating the results. Since a special gun with a high twist of rifling was not available for this round the computed curve could not be compared with empirical data of rounds fired under proper spin conditions.

B. Caliber .30 Ball M2

This bullet is normally fired from a gun with a twist of 1 turn in 10 inches (25.4 cm), at a muzzle velocity of 854 m/sec. Data on the seven rounds fired for this program are found in Tables I and II and Figures 7 and 8. Three of the rounds were fired at a reduced muzzle

velocity, approximately 500 m/sec from the standard Mann barrel. They developed 33° to 42° maximum yaw at 1.1 meters from the tipping plate. The measured location of the maximum yaw agrees with the computed value. However the bullets had approximately 60 percent of the spin which they would have had at this impact velocity if they were fired at standard muzzle velocity.

To show the effect of spin on the period and magnitude of yaw, four rounds were fired at approximately the same muzzle velocity from a gun with a twist of 1 turn in 6 inches (15.2 cm) which is a 60 percent faster twist than the standard barrel. Three of these rounds with normally spaced impacts on the tipping plate developed 11° to 17° yaw at 0.64 meters. This measured half-period of yaw agrees with the computed value. The fourth round (Rd. 8632) in this group impacted on the plate close to a hole from a previous round. This accidental lack of homogenuity of the resisting plate gave three times as much yaw but the period of yaw remained the same.

There is good agreement between the location of the maximum yaw and the computed values for all seven rounds. Only those rounds fired from the high twist barrel properly simulate the impact conditions at 500 m/sec.

C. 7.62 mm M-59

This bullet is normally fired from the M-14 rifle which has a twist of 1 turn in 12 inches (30.5 cm), at a muzzle velocity of 869 m/sec. Four rounds were fired from this gun at reduced muzzle velocity, approximately 600 m/sec. Data on these rounds are found in Tables I and II and Figures 9, 10 and 11. These rounds developed 44° to 53° maximum yaw at 3.0 to 3.4 meters from the tipping plate. The measured distances show good comparison with the computed value, 3.4 meters.

The small differences between the observed location of the maximum yaw and the computed value for the half-period of yaw can be attributed

to some combination of the following factors. The bullet is slightly deformed on impact. If the steel core drives forward into the copper shell, the shift in the center of mass with respect to the center of pressure could decrease the static moment coefficient and shorten the period. There are also small changes in the moments of inertia due to the impact. Under this condition of impact the gyroscopic stability factor is low (1.3) and the period length is very sensitive to small changes in the bullet parameters.

An M-59 bullet fired at standard muzzle velocity will strike a target 343 meters away at 600 m/sec. The spin would be 0.20 rad/caliber and the gyroscopic stability factor would be 1.8. To simulate this spin and stability condition at a reasonable test distance from the gun muzzle, a barrel with a twist of 1 turn in 9.5 inches (24 cm) is required. Since this gun was not available, another test condition was selected. Four rounds were fired from a gun with a twist of 1 turn in 6 inches (15.2 cm). The spin at the muzzle was 0.32 rad/caliber. This gun gave the bullets more spin than the normally fired bullet would have had at the impact velocity. Two rounds fired at the tipping plate developed 16° maximum yaw at 0.74 meters from the plate. Two other rounds impacting on the plate at a greater angle to the trajectory (20°) developed 30° to 35° yaw at the same distance.

Under actual impact conditions at this velocity a bullet fired at standard muzzle velocity would have a period and magnitude of yaw between the values observed in these two test conditions. The maximum yaw would occur at 1 meter from the tipping plate.

The period of yaw of a bullet decreases in length as the bullet velocity decreases and the range increases. This is shown in Figure 11. The solid line is the computed curve for a round fired at standard muzzle velocity from the M-14 rifle. The points on the graph are data for rounds fired at a reduced muzzle velocity. These data[8] were obtained at approximately 30 to 40 meters from the muzzle.

D. 7.62 mm M-80

Three rounds were fired at reduced muzzle velocity, approximately 600 m/sec, from the M-14 rifle, Figures 12 and 13. One round developed its maximum yaw at 1.5 meters from the tipping plate. This agrees with the computed value for this impact condition. Two rounds developed their maximum yaw at 2.1 meters from the tipping plate. This represents a significant difference of the measured half-period (40 percent increase) from the computed value. There is no evidence of a large loss in spin due to impact. To explain this difference in the half-period would require at least a 10 percent favorable change in the values of the moments of inertia and the static moment coefficient used in the computations. Some of this variation can be accounted for by changes in shape due to impact. Figure 12 shows the rounds in flight after impact and a typical round before impact. If we discount the slight tilt to the méplat, Round 8016 looks more like the bullet shape before impact. Some slight bulging exists where the ogive joins the body. Rounds 8017 and 8018 have a smoother transition where the ogive joins the body, more like the M-59 bullet. The M-80 and the M-59 have the same dimensions up front before they are fired[8]. The picture before impact suggests that some deformation to the M-80 bullet must occur in the gun barrel. The action of the tipping plate could swage the bullet, increasing the transverse moment and decreasing the axial moment. Both effects would contribute to an increase in the period.

E. 7.62 mm M-61

Two rounds were fired at reduced muzzle velocity from the M-14 rifle, simulating at the test location an impact velocity of approximately 600 m/sec, Figures 14 and 15. Both rounds developed 48° yaw at 2.4 meters from the tipping plate, 0.6 meter less than the computed value. Some of the difference between the empirical data and the computed length of the half-period can be attributed to the deformation of the steel core bullet. Since the gyroscopic stability factor is low (less than 1.3) for the undamaged bullet under this firing condition,

small changes or variations in bullet physical parameters cause large variations in the period. When the spin is also simulated at the test condition, the stability is higher and the period shorter. Maximum yaw should develop at approximately 1 meter from the tipping plate.

F. Caliber .50 Ball M2

Five rounds were fired from a Mann barrel with a standard twist of rifling at reduced muzzle velocity to impact at approximately 600 m/sec, Figures 16-18. Three rounds penetrated a Duraluminum 6061T6 tipping plate and developed about 45° maximum yaw. Two rounds against a softer plate Duraluminum 2024-0 developed only 20° to 35° maximum yaw. The location of the maximum yaw for the latter two rounds agrees with the computed value, 2.9 meters. For the harder plate the location of the maximum yaw moved closer to the tipping plate, 2.5 meters, a 14 percent decrease. For two of the rounds in the harder plate, part of this decrease in period is due to the greater velocity loss due to impact, which accounts for a 4 percent decrease. The remaining 10 percent must be attributed to changes in bullet parameters. Like the M-59 and the M-61 bullets the cal .50 Ball M2 has a steel core. All three bullet types were deformed by the plate causing a decrease in the period.

This round would have developed its maximum yaw closer to the tipping plate if the spin had been properly simulated for the impact velocity. It is estimated that with the proper spin the undamaged round at 600 m/sec impact velocity would develop its maximum yaw at 1.7 meters after the tipping plate.

G. Caliber 5.56mm, M-193

Six rounds of this bullet type[9] were fired from a M16 rifle, with a twist of 1 turn in 12 inches (30.5 cm). The muzzle velocity was reduced to give impact velocities of approximately 750 and 500 m/sec. These data are discussed here even though the yaw card technique is not considered satisfactory for this bullet. The impulsive torque

imparted by the yaw card appears to be large enough, compared with other bullet parameters, to affect noticeably the yaw magnitude and period. The results given here show how an old and tested technique for measuring the yawing motion can give unsatisfactory data. No particular search was made for a yaw card so light that it would not affect the bullet motion. Photographic techniques are obviously superior for getting this type of data. However the field of view of the existing spark photographic stations is not large enough to get pictures because of the large dispersion of the round after impact.

Three of the rounds were fired to strike the tipping plate at approximately 750 m/sec. These rounds should have developed their maximum yaw at about 1.5 to 1.6 meters from the tipping plate. The stability factor at impact is about 1.5 and the period of yaw is very sensitive to changes in bullet parameters. The length of the period of yaw for round 8007 was computed with the spin term as the only variable. At the muzzle, where the spin is essentially the twist of rifling, the half-period is 2.0 meters. At 16 meters from the muzzle where the tipping plate was located, ν is larger and the half-period decreases to 1.8 meters. Due to impact on the plate, which produces another velocity loss, ν increases again and the half-period is about 1.5 meters. The observed location of the maximum yaw was 2.4 meters, 50 percent greater than the computed value. Like the M-80 and the cal .30 Ball M2 bullets, this round has a solid lead core. It has been observed that the deformation of this type of bullet on impact appears to change the pertinent parameters to cause an increase in the yaw period. Since the stability factor is lower for the M-193 bullet (1.5) the effects of deformation cause greater changes in the period.

Three rounds were fired to strike the tipping plate at approximately 550 m/sec. The computed half-period for Round 8012 are: at the muzzle, 2.5 meters; just before impact, 2.0 meters; after impact 1.4 meters. Before the plate, the period is larger than the previous group because of the effect of $C_{M\alpha}$. After the plate, the period is shorter

because of the greater velocity loss due to impact. The stability factor at impact was about 1.2 and the yaws at impact were large, up to 13°. Under this condition the assumption that a minimum yaw occurs at the plate is no longer valid. Large impulsive torques developed because of the large impact yaw. The response of the bullet was greater because of the low stability factor. Both the impulsive torque imparted by the yaw cards and the static moment coefficient have a functional dependence on the magnitude of yaw. When the yaw is over 30° it is difficult to assign a reasonable value to $C_{M\alpha}$. The asymmetry of the yaw graph, Figure 26, narrow at low yaw values and wide at high yaws, is due to this dependence of the moments on the yaw magnitude.

VII. CONCLUSION

Existing ballistic theory of the motion of a yawing projectile can be used to predict the location of the first maximum yaw after an impulsive torque is applied to the bullet. To use the equations, it is necessary to know the spin, moments of inertia and the static moment coefficient after impact. Numerical values are generally available for the undamaged bullet in flight at low yaw magnitudes. When damage to the bullet is not too severe, estimates of changes to these numerical values can be made.

There is some evidence that the effect of impact on the parameters that control the yaw period is different for bullets with steel cores and bullets with lead alloy cores. The observed period of yaw after impact was slightly shorter than the period of the undamaged free flight condition for bullets with steel cores. This can be explained if we assume that the steel core drives forward into the copper shell, moving the center of mass forward, while the center of pressure which represents the external shape of the copper shell changes very little. This causes a decrease in $C_{M\alpha}$. The redistribution of mass in the solid lead alloy bullets appears to influence the parameters so as to increase the yaw period. For those bullets tested, the swaging action of the tipping

plate would tend to increase the transverse moment of inertia and decrease the axial moment of inertia.

Any investigation of the motion of a bullet after impact should take the precaution to simulate properly the spin at the impact velocity. The response of the bullet to the impulsive torque at impact is a function of the bullet spin, the moments of inertia and the static moment coefficient. The common method of testing low impact velocities by reducing the muzzle velocity can give erroneous data unless gun barrels with a special twist of rifling are used. The length of the yaw period for spin conditions other than the test conditions can be computed for gyroscopically stable bullets, provided (a) bullet deformation is not a function of impact spin; (b) reasonable estimates for changes of moments of inertia can be made for the deformed bullet; (c) estimates of the functional dependence of $C_{M\alpha}$ on the yaw can be made for very large values of yaw (over 45°). To compute the magnitude of yaw for spin conditions other than the test condition from the test data would also require that the impulsive torque is not a function of bullet spin. There is some empirical data that at the higher spin rates the magnitude of yaw is less.

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APPENDIX - ILLUSTRATIONS

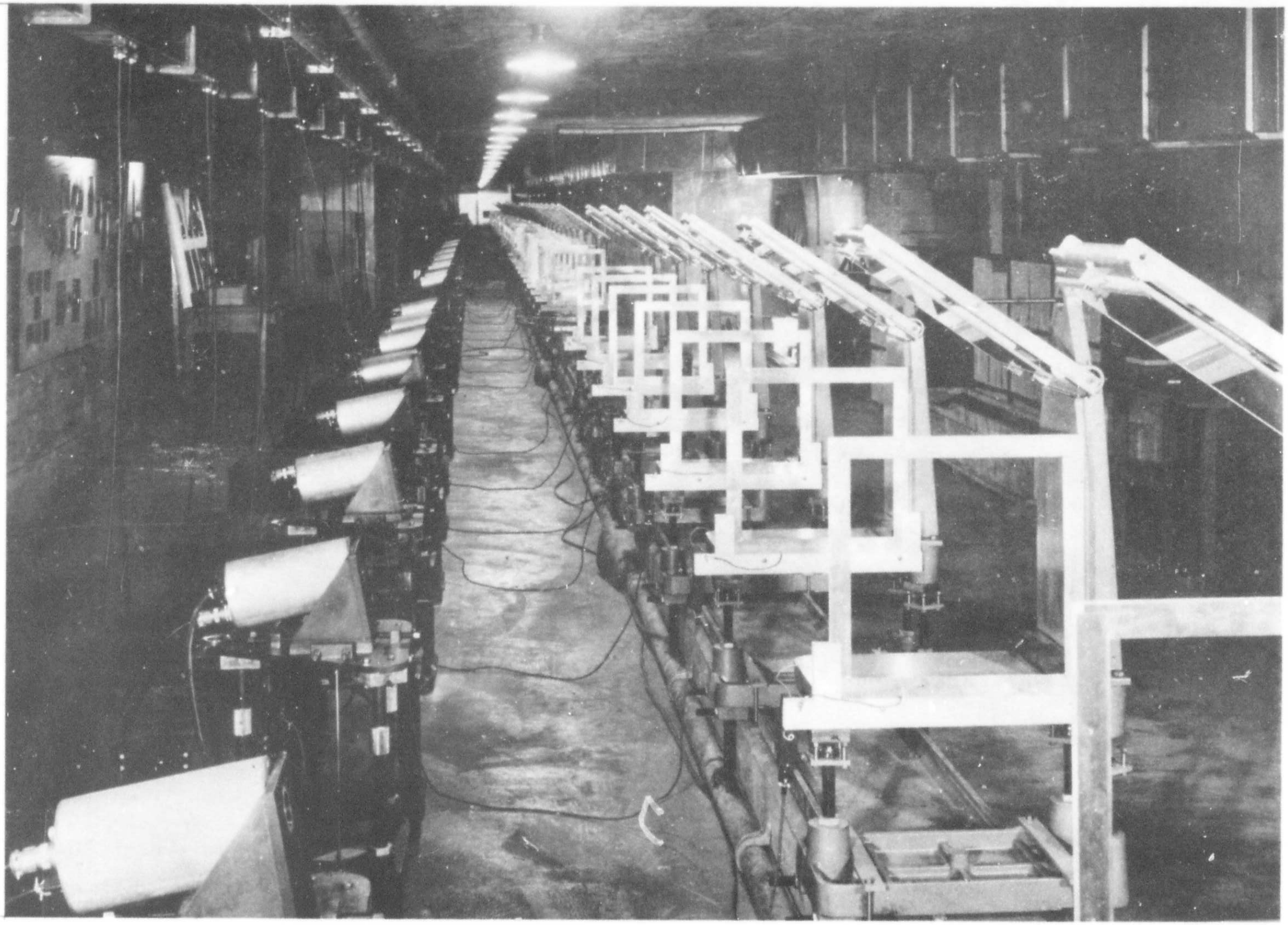
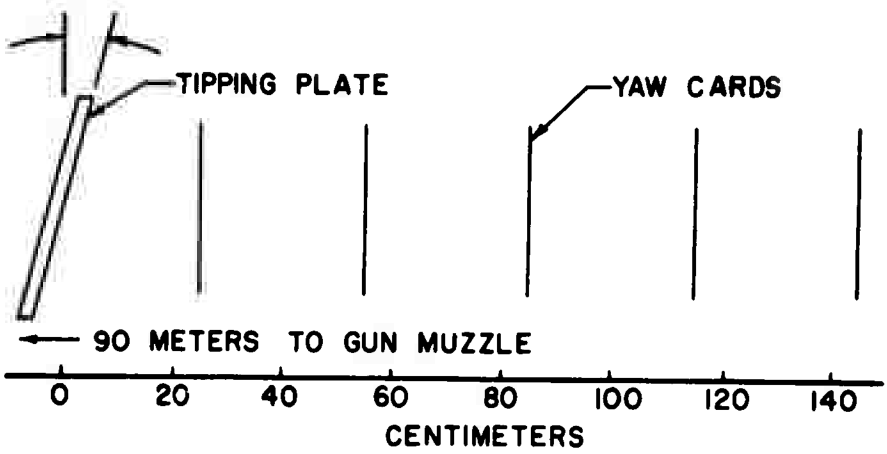


Figure A-1. The Free Flight Aerodynamics Range

14.5 MM A.P.I.



7.62 MM, CAL. .30, CAL. .50, CAL. .223

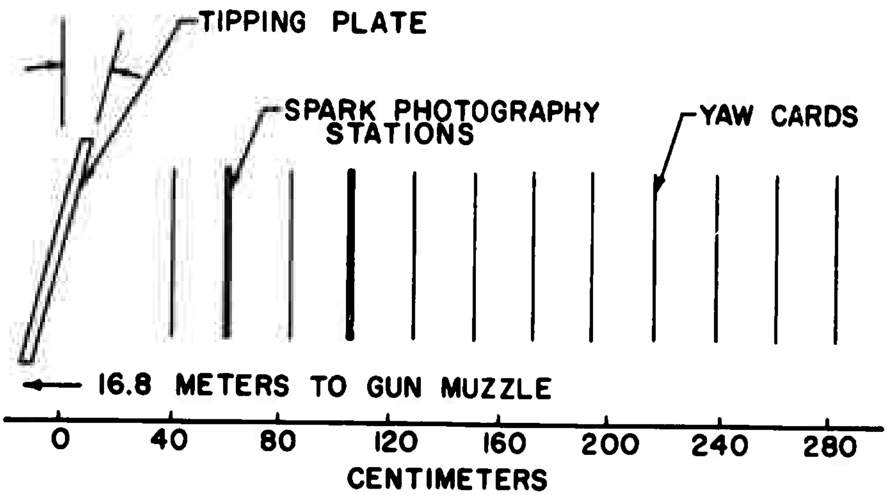


Figure A-2. Location of Tipping Plate and Yaw Cards in the Range.

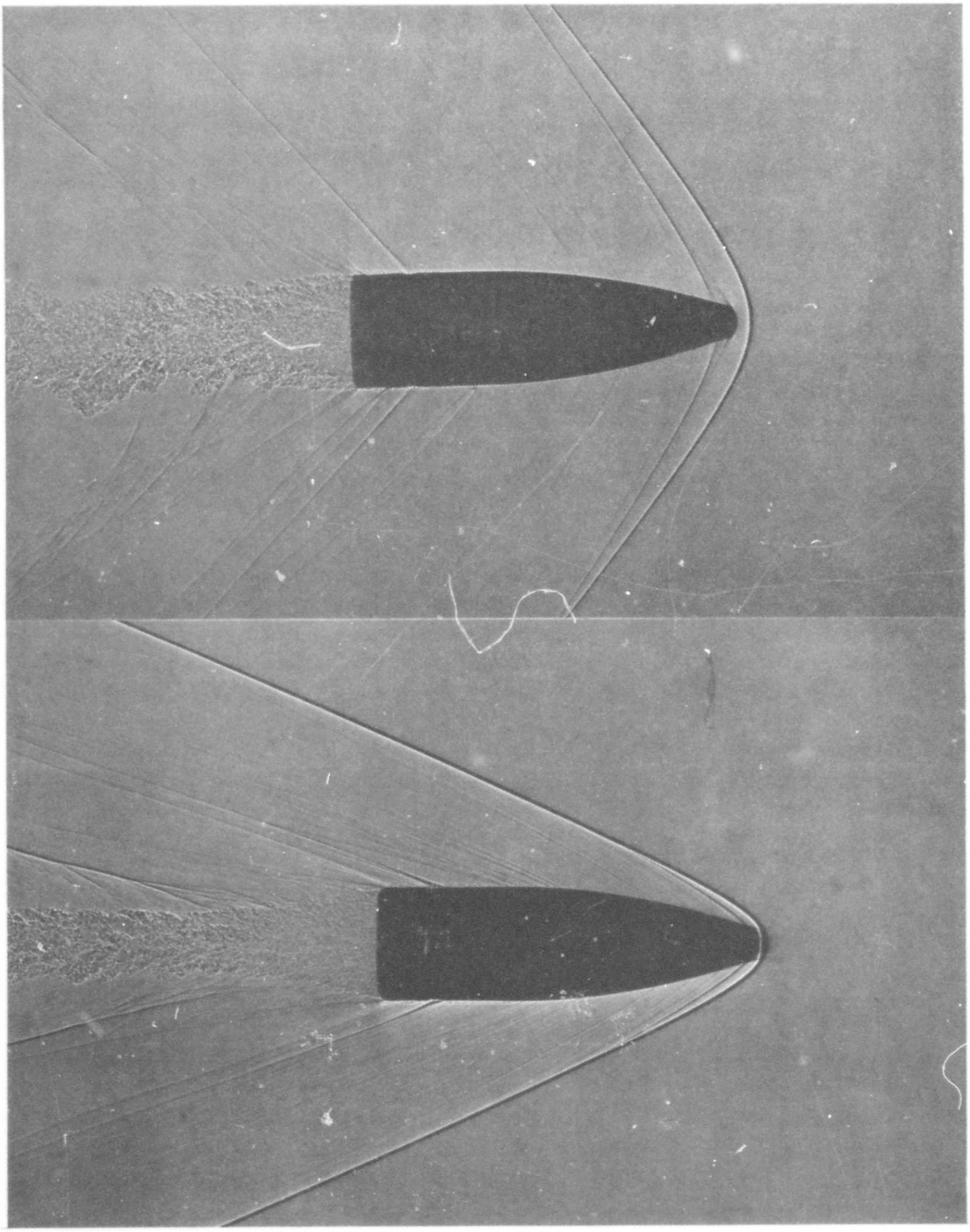


Figure A-3. 14.5 MM API; Rd.7755, Velocity 434 m/sec; Rd. 7764, Velocity 962 m/sec.

14.5 MM A.P.I.

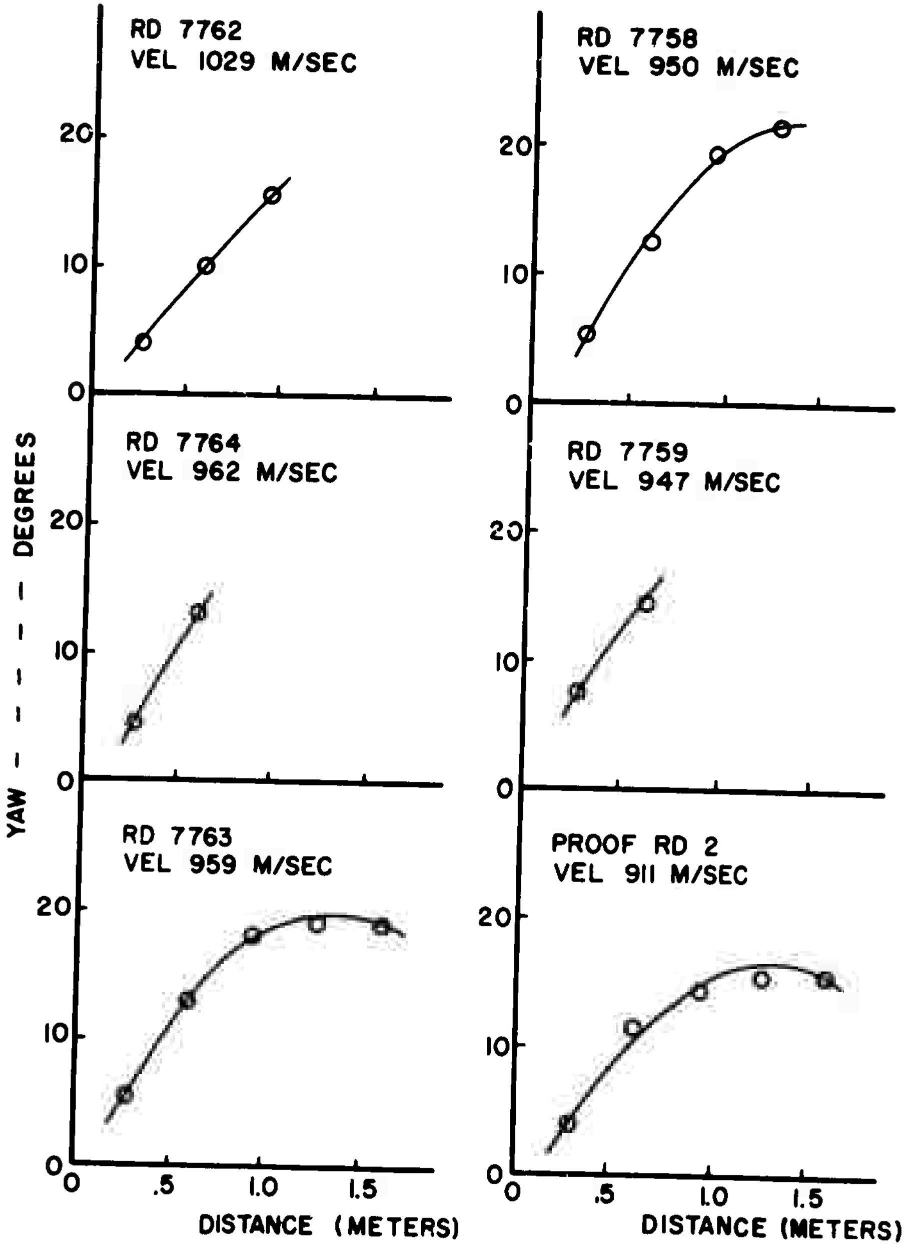


Figure A-4. 14.5 MM API, Yaw vs. Distance from the Tipping Plate.

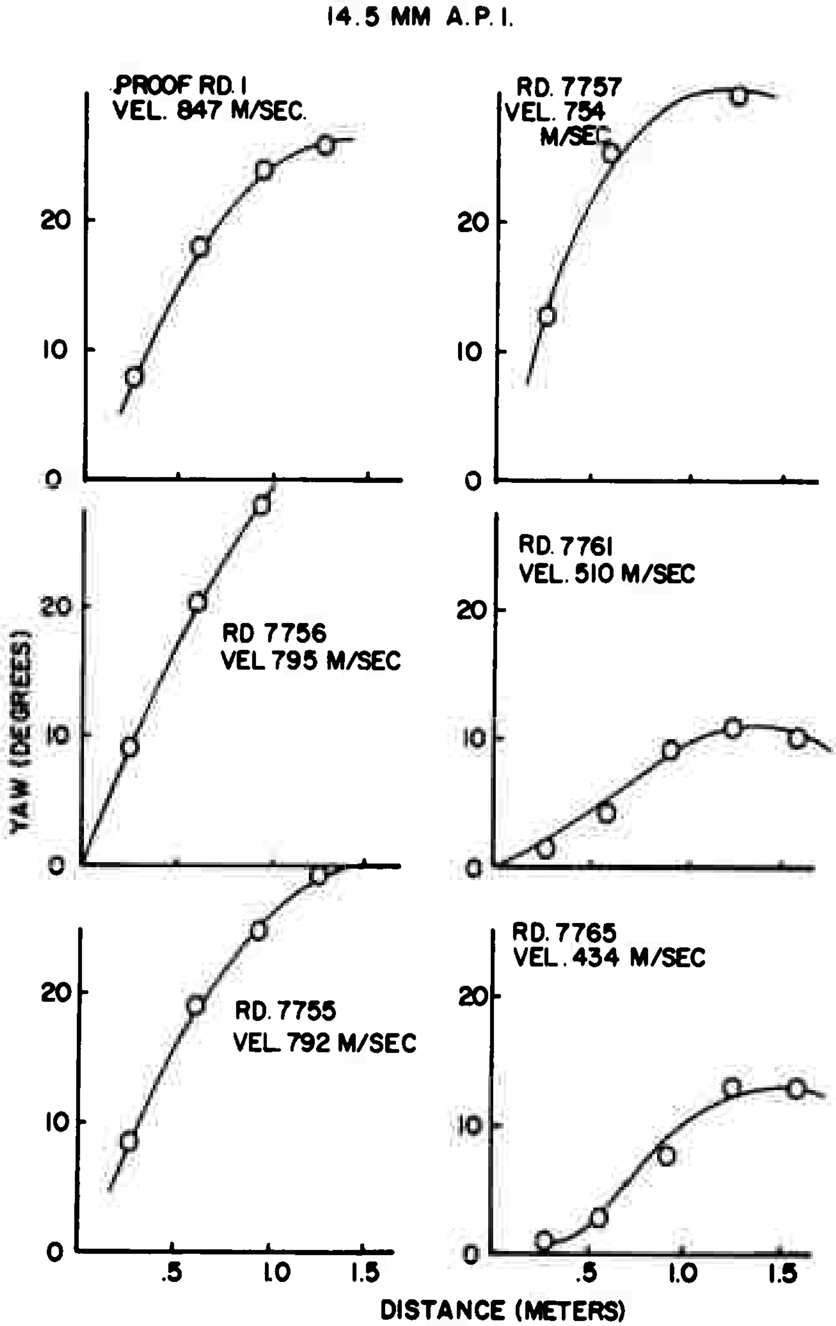
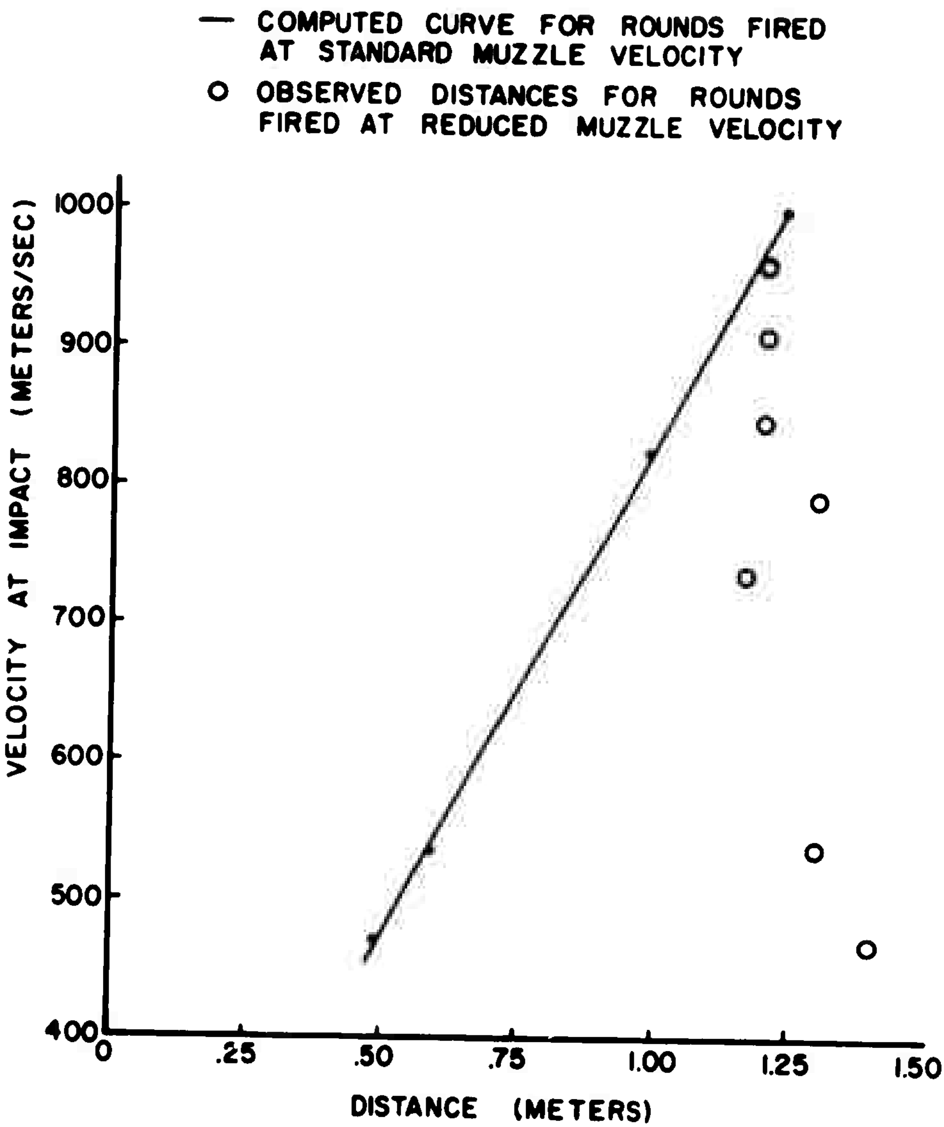


Figure A-5. 14.5 MM API, Yaw vs. Distance from the Tipping Plate.

14.5 MM A. P. I.



Fi[illegible] A-[illegible]. [illegible] MM API, L[illegible] [illegible] F[illegible] Maximum Yaw After Impact [illegible] Impa[illegible] [illegible]ity.

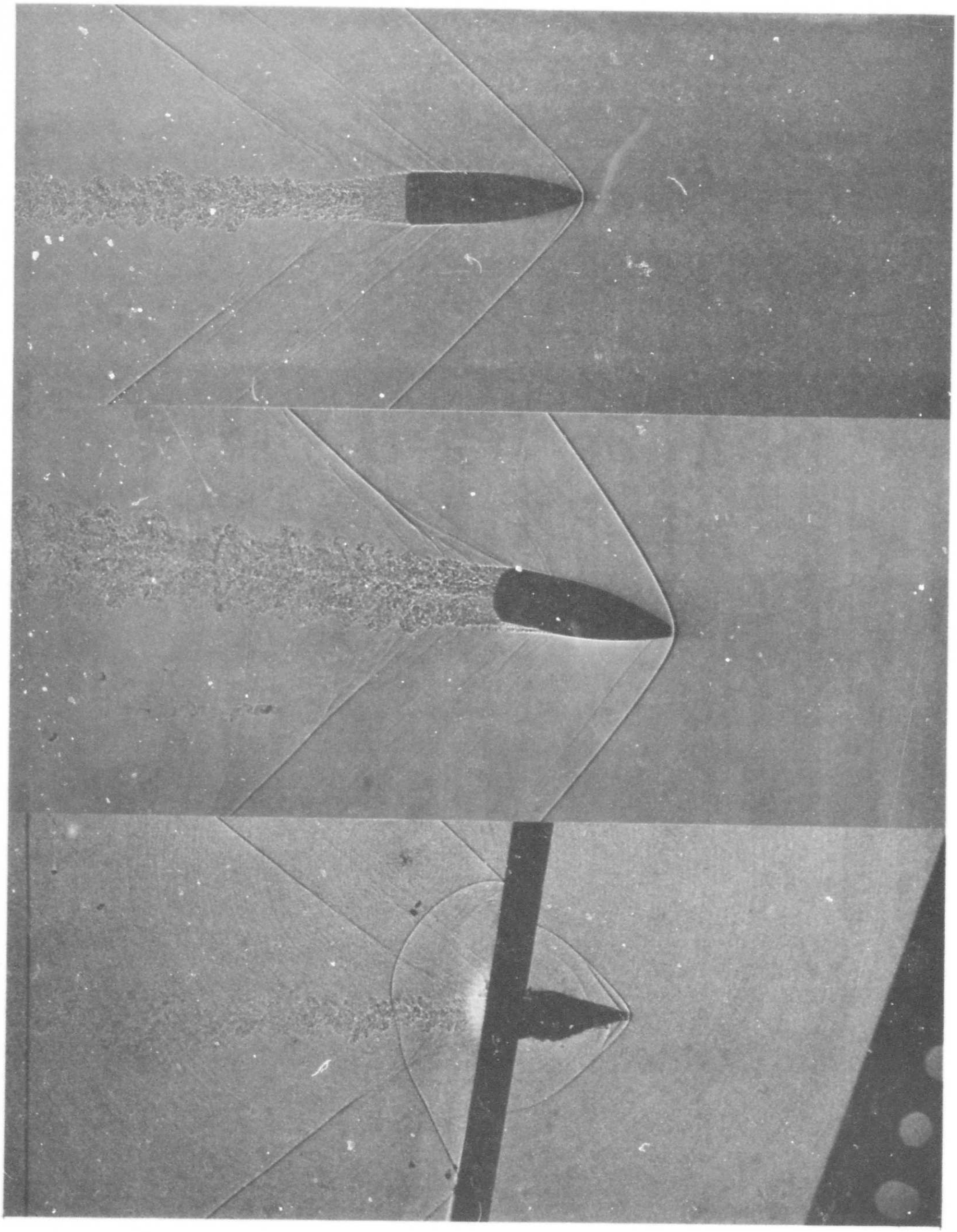


Figure A-7. Cal .30 Ball M2: Rd. 8634, Velocity 530 m/sec - Free Flight; Rd. 8014, Velocity 463 m/sec - After Impact; Rd. 8631, Velocity 531 m/sec - At Impact.

CAL. .30 BALL M2

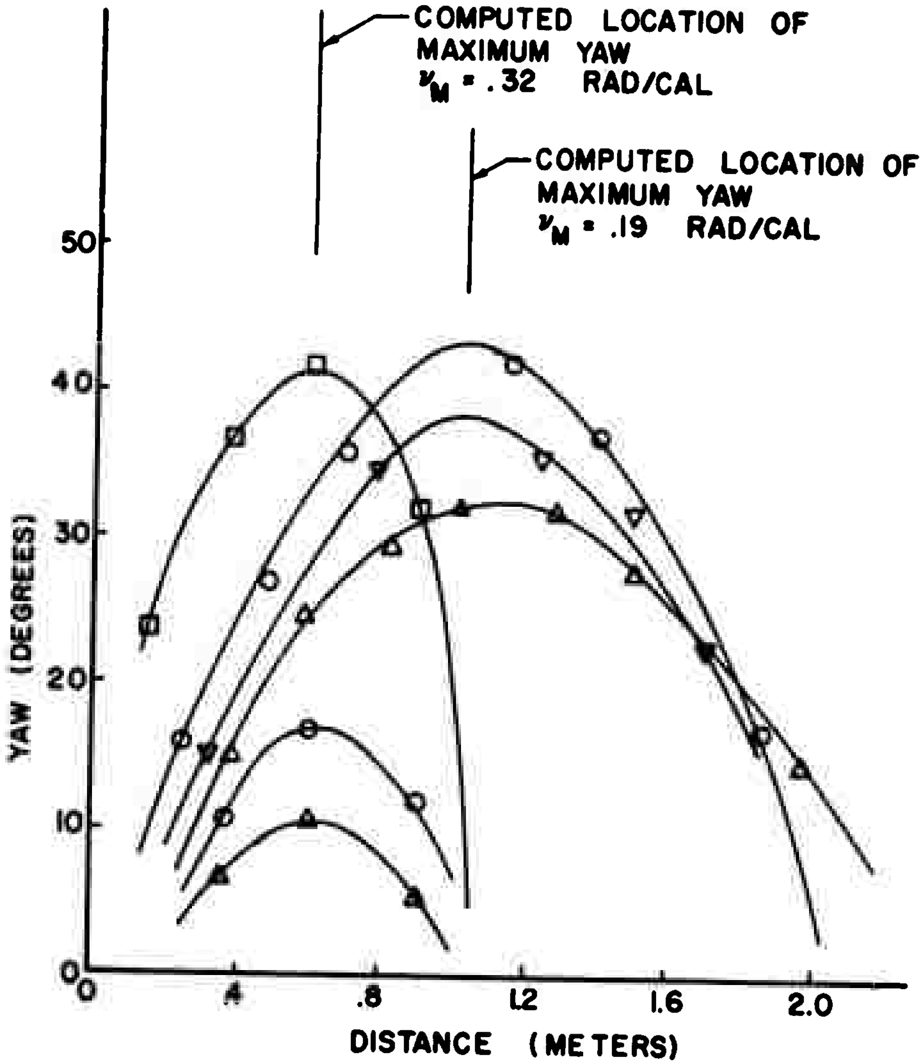


Figure A-8. Cal .30 Ball M2, Yaw vs. Distance from the Tipping Plate.

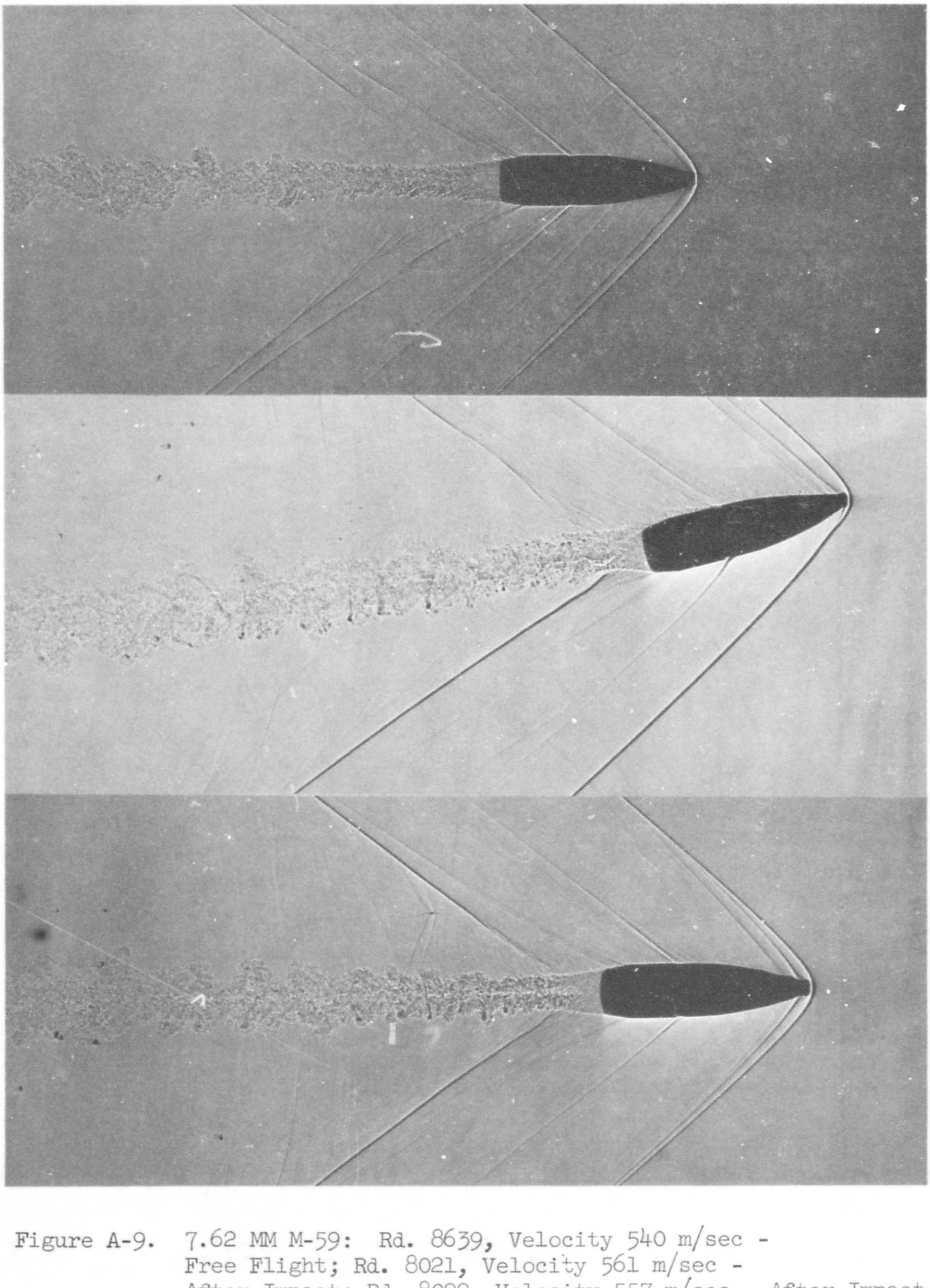


Figure A-9. 7.62 MM M-59: Rd. 8639, Velocity 540 m/sec - Free Flight; Rd. 8021, Velocity 561 m/sec - After Impact; Rd. 8022, Velocity 557 m/sec - After Impact.

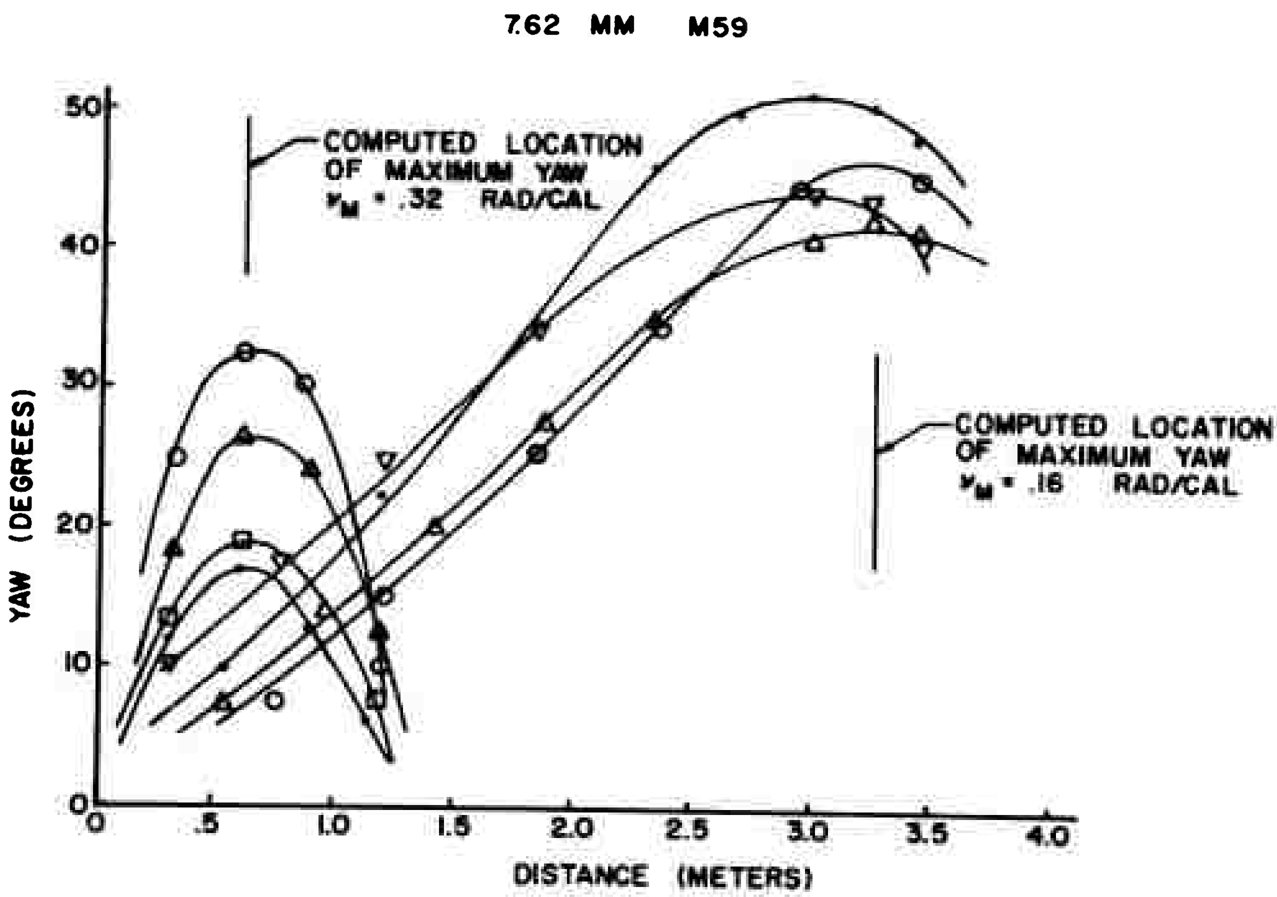


Figure A-10. 7.62 MM M-59, Yaw vs. Distance from the Tipping Plate.

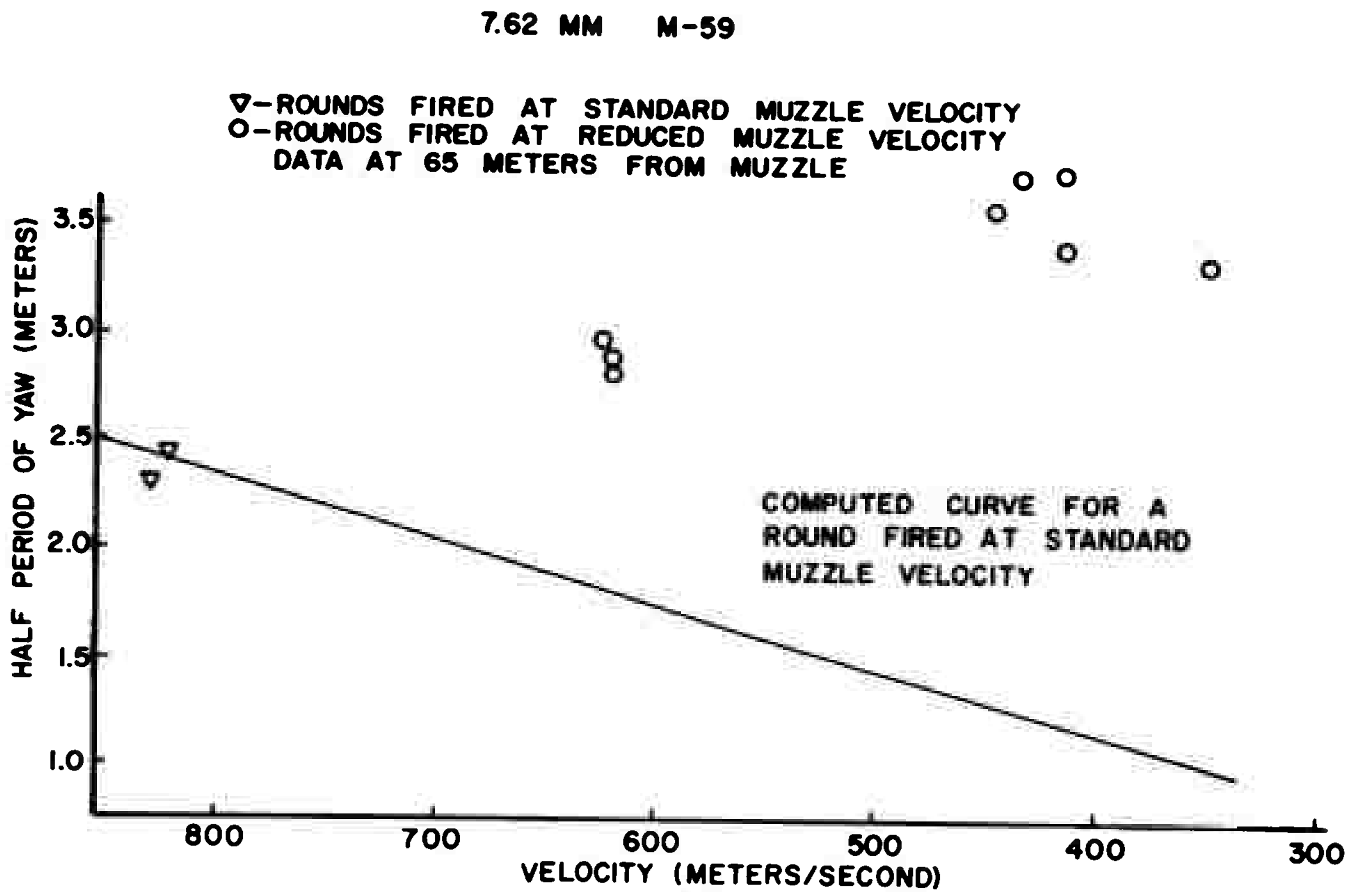


Figure A-11. 7.62 MM M-59, Effect of Bullet Spin on Yaw Period.

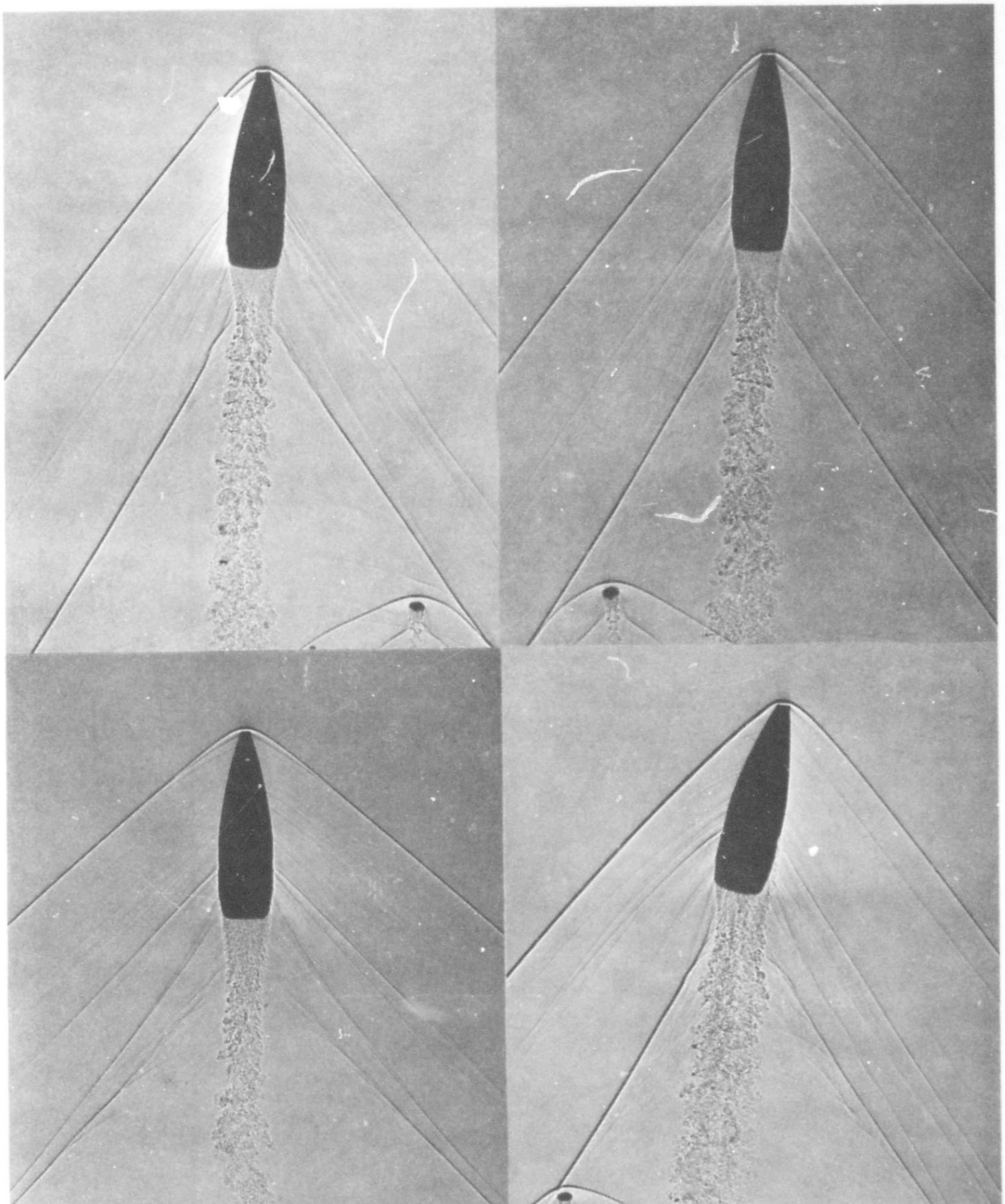


Figure A-12. 7.62 MM M-80: Rd. 6542, Velocity 600 m/sec - Free Flight; Rd. 8016, Velocity 592 m/sec - After Impact; Rd. 8018, Velocity 604 m/sec - After Impact; Rd. 8017, Velocity 598 m/sec - After Impact.

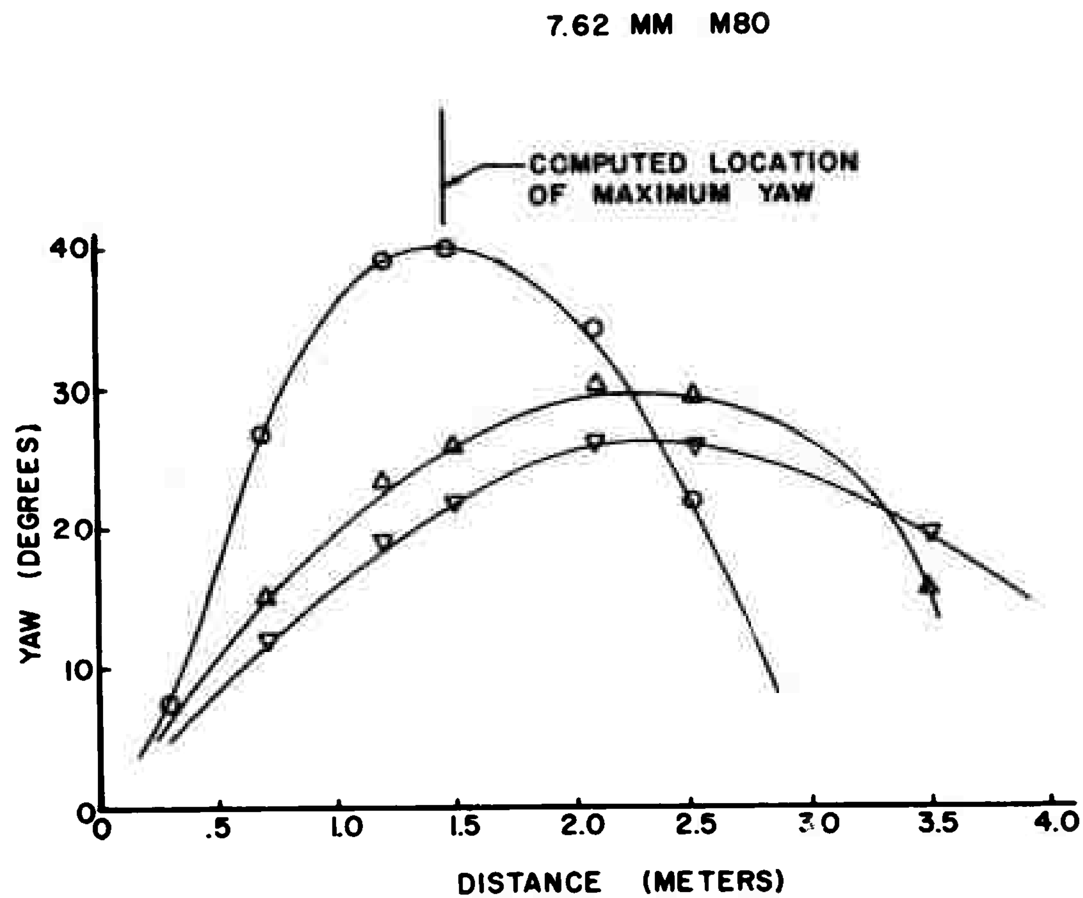


Figure A-13. 7.62 MM M-80, Yaw vs. Distance from the Tipping Plate.

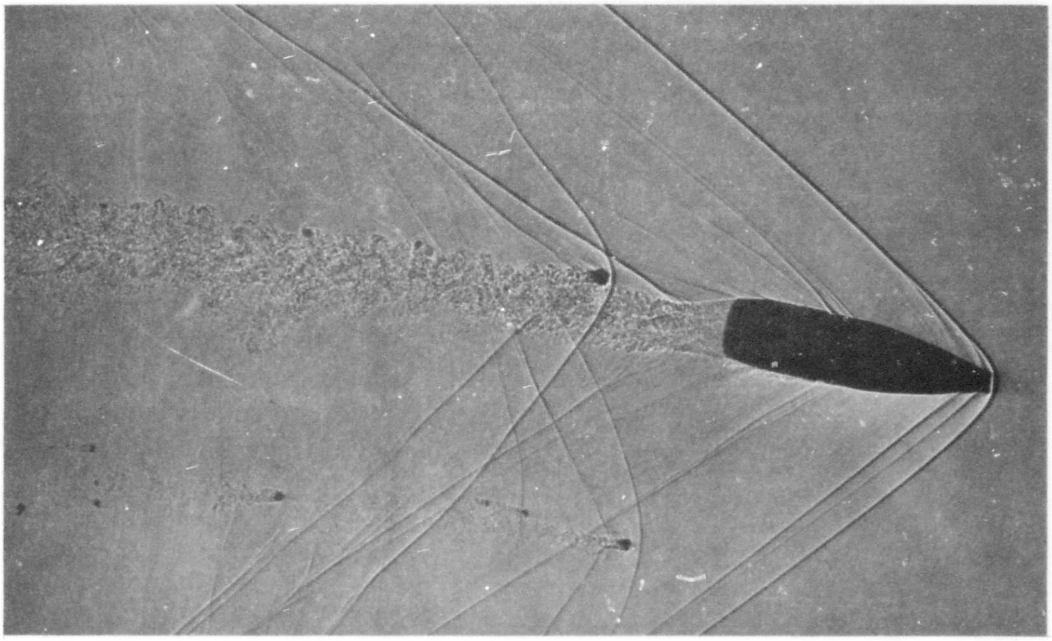


Figure A-14. 7.62 MM M-61, Velocity 599 m/sec - After Impact

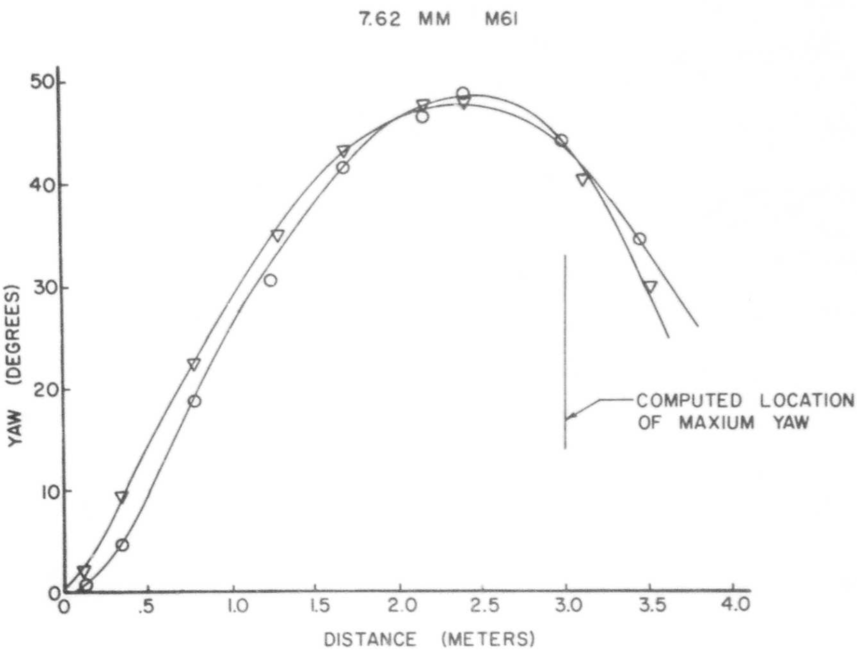


Figure A-15. 7.62 MM M-61, Yaw vs. Distance from the Tipping Plate.

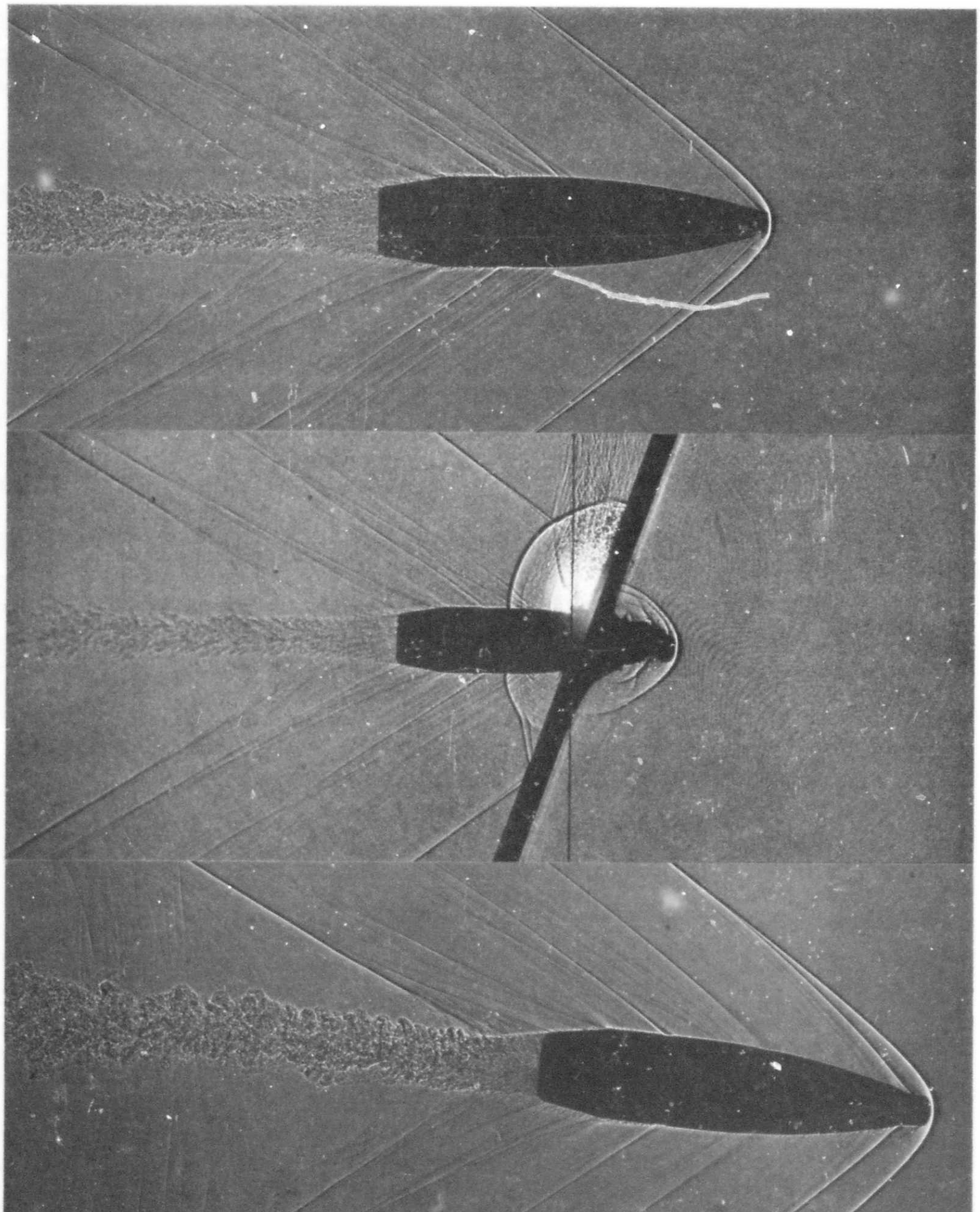


Figure A-16. Cal .50 Ball M2: Rd. 8625, Velocity 620 m/sec - Before Impact; Rd. 8625, Velocity 616 m/sec - At Impact; Rd. 8625, Velocity 611 m/sec - After Impact.

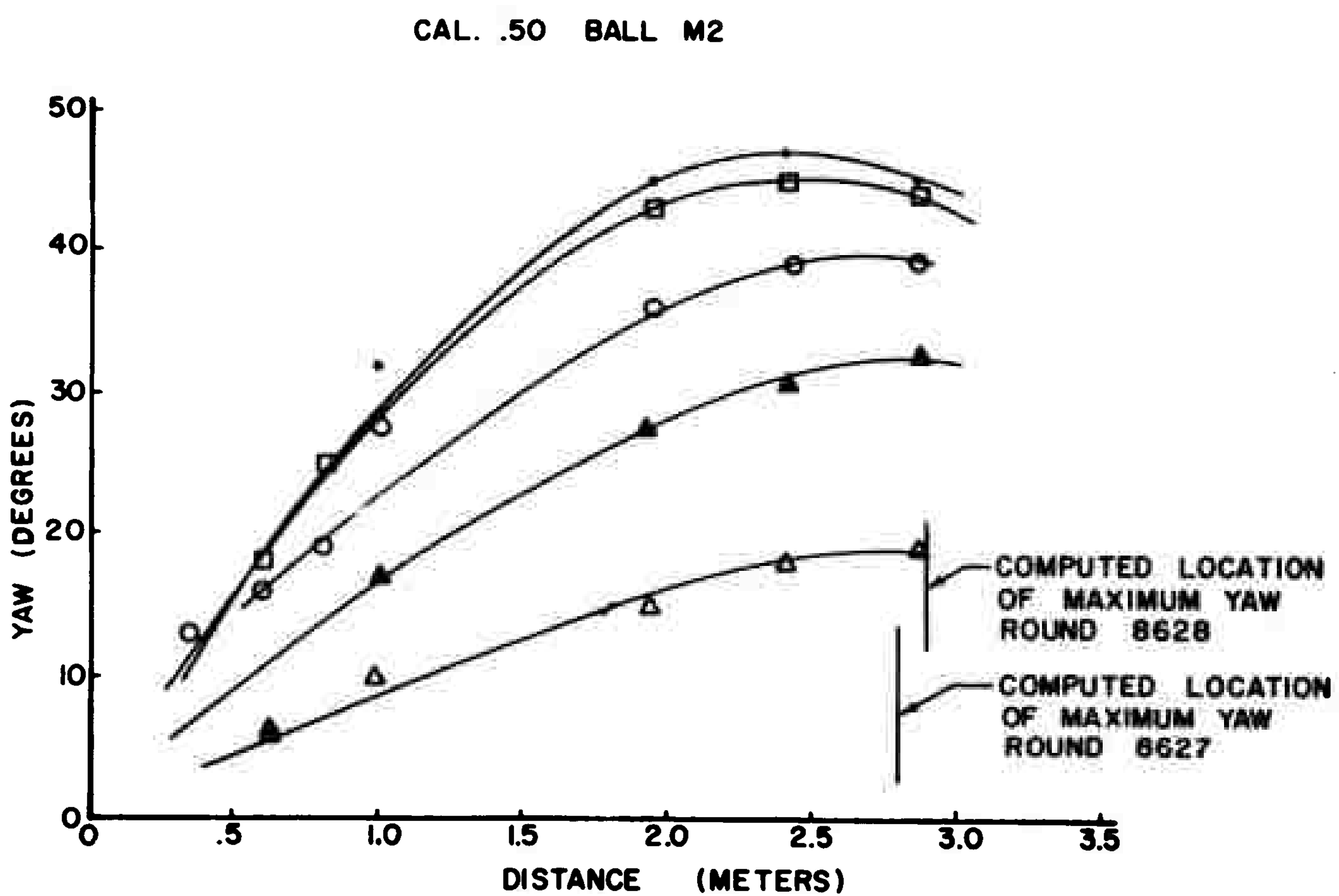


Figure A-17. Cal .50 Ball M2, Yaw vs. Distance from the Tipping Plate.

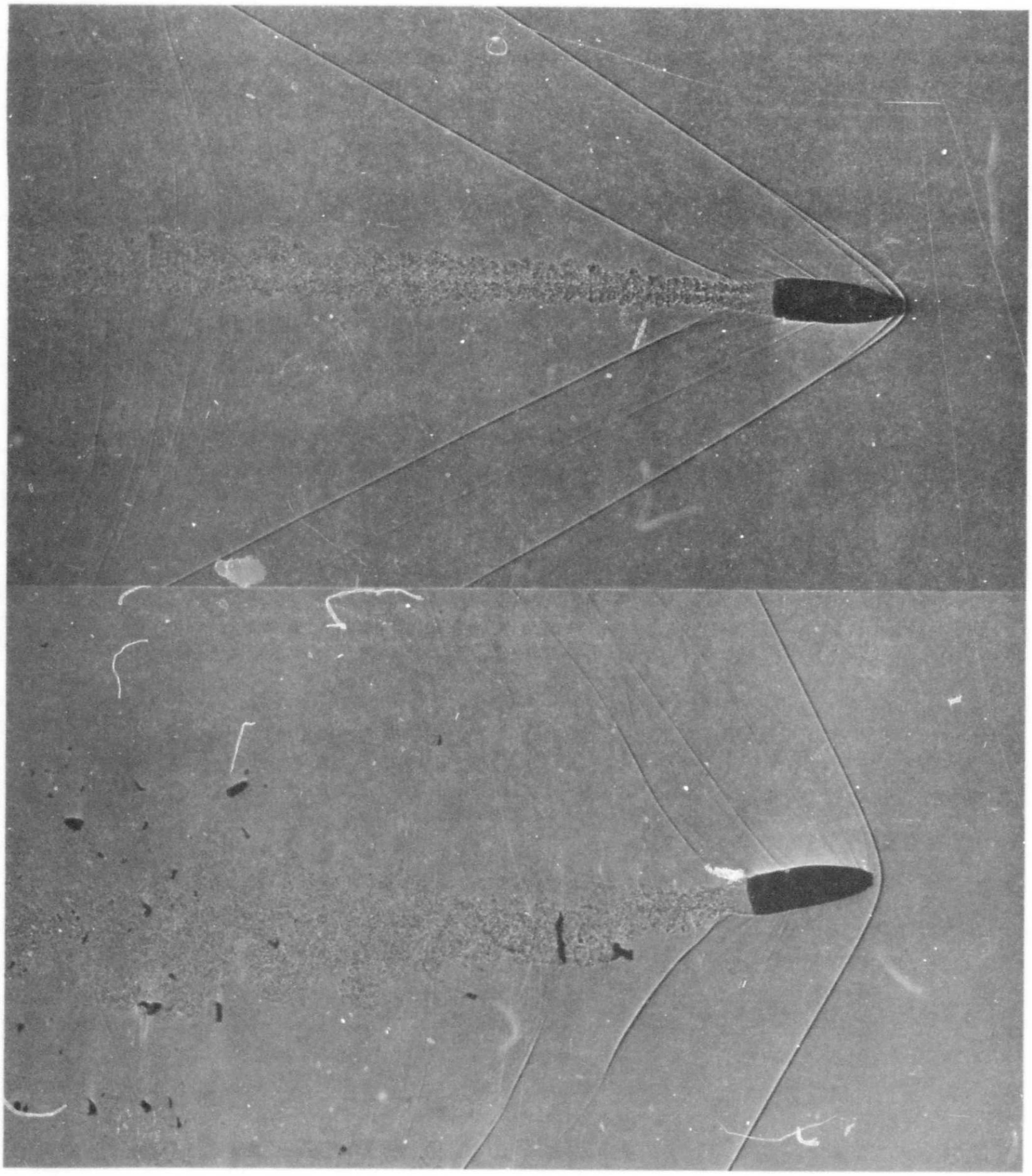


Figure A-18. 5.56 MM M-193: Rd. 8007, Velocity 678 m/sec - After Impact; Rd. 8012, Velocity 411 m/sec - After Impact.

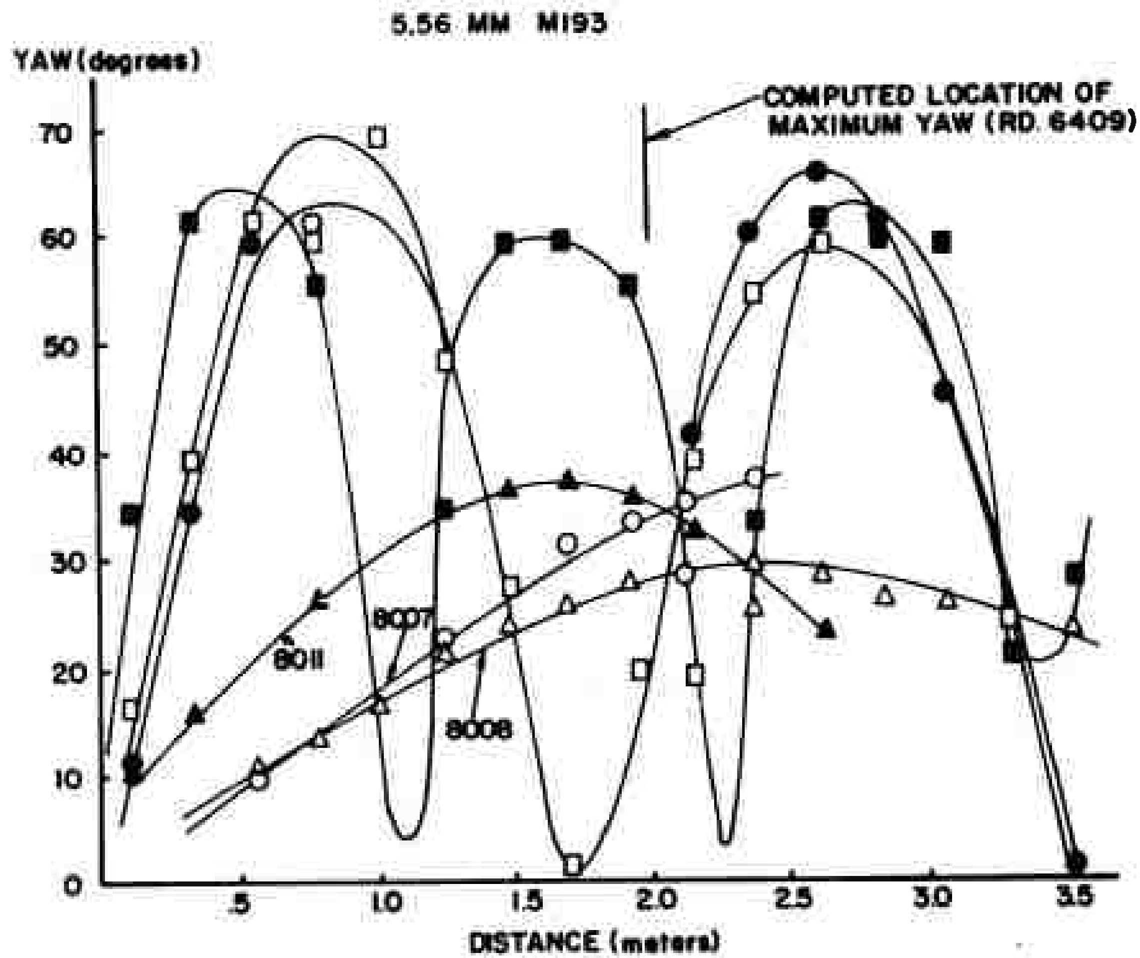


Figure A-19. 5.56 MM M-193, Yaw vs. Distance from the Tipping Plate.

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13. ABSTRACT

When a bullet penetrates a thin plate and emerges relatively undamaged, the period of the subsequent yawing motion can be predicted from a knowledge of the physical constants of the bullet, the spin, the density of the medium after penetration and the static moment coefficient. The equations used to predict this motion are given. Several examples of the predicted motion are compared with empirical data. The effects on the period and the magnitude of yaw of small changes in the bullet characteristics due to impact on the plate are discussed, emphasizing the importance of obtaining sufficient data to describe the complete yaw period and sufficient information on the physical integrity of the bullet after impact. The importance of imparting the correct bullet spin when simulating real down-range test conditions is discussed. A comparison of test data taken under different spin conditions is given.

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Tipping Plate Yaw after Impact Vulnerability						